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How accurately can we determine stellar parameters. The case of T_{eff} in cool stars.

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Abstract. The determination of stellar effective temperature is one of the most crucial items, when turning to investigate stellar evolution and element abundances. We address the question of how accurately this parameter can be determined from the view of model insecurities.

We conclude, that it is not possible to assign a single value of model dependent error to each method of T_{eff} determination. It is nevertheless obvious, that error bars smaller than 75 K are unlikely.

1. Introduction

Accurate stellar parameters are a fundamental ingredient to various important analysis in astronomy. The accuracy of stellar age determination through the comparison with modeled evolutionary tracks as well as the determination of the abundance of the various elements prominent in stars crucially depends on the input set of stellar parameters.

This paper addresses the errors in the determination of effective temperatures as one of the most important stellar parameters.

As shown by Gehren et al. (2004) for a mildly metal poor turnoff star, an insecurity of ±100 K in effective temperature leads to an insecurity in age of ±1.5 Gyrs. For element abundance measurements of main sequence stars, typical uncertainties corresponding to an error of ±100 K in effective temperature are between ±0.02 and ±0.15 Dex depending on T_{eff} and the element investigated (see e.g. Shen et al (2005)).

The process of stellar parameter determination is hereby similar for all parameters and all methods available to determine these parameters. Normally one starts with a *first guess* set of stellar parameters such as effective temperature (T_{eff}), surface gravity ($\log(g)$), metallicity ([M/H]), micro turbulence parameter (ξ_{micro}). In the next step the corresponding model atmosphere is calculated. Based on this atmosphere the overall flux distribution is determined and integrated in order to obtain colors, or single lines are synthesized to make use of their dependency on the input parameters. After a comparison of these theoretically obtained properties to the measurement a new set of stellar parameters is fixed and this process is iterated to a reasonable level of convergence.

For many *users* the steps of model atmosphere calculation and determination of the theoretical quantities such as colors, equivalent widths or line profiles might be hidden in the use of tabulated data. Nevertheless the described procedure is intrinsically tied to the tabulated data.

The model atmospheres used in the process of stellar parameter determination can therefore be called the **backbone** of the procedure. Any parameter determination can not be more trustworthy and accurate than the stellar atmospheric model it is based upon. This holds true for the Infrared Flux Method (IRFM) for stellar effective temperature measurement, that is sometimes said to be model independent, but, as shown by Megessier (1994) and Grupp (2004b), is not.

2. Sources of insecurities

In this paper we will concentrate on the influences of the insecurities in modeling the stellar atmosphere and in calculating stellar line profiles. We will completely ignore insecurities that come into play by observation.
All values given for errors belong to our standard solar model.

2.1. Model atmospheres

We are using the model atmosphere codes MAFAGS-ODF and MAFAGS-OS described by Grupp (2004a). This code is similar to the more commonly used codes ATLAS (Kurucz (1979)) and MARCS (Edvardsson et al. (1993)).

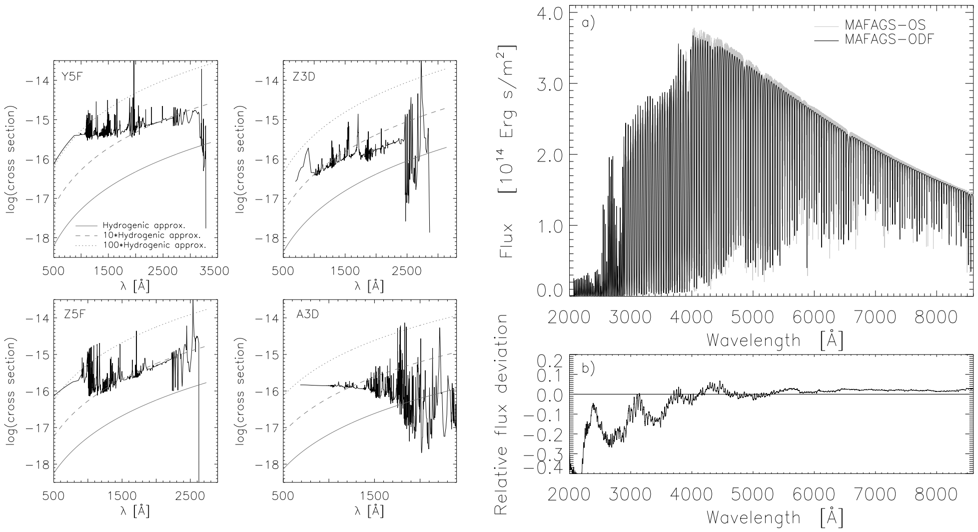
The basic assumptions of our model are: 1D hydrostatic plane parallel layers, no time dependent processes, local thermal equilibrium (LTE), no chromosphere nor corona and flux conservation throughout the atmosphere.

Opacity data In stellar atmospheric models we can distinguish between two types of opacity sources. The first is related to bound-bound processes, the so called *line opacity*. The second is related to bound-free and free-free processes and can be summarized under the keyword *continuous opacity*.

There are essentially two methods of treating line opacity in stellar atmosphere codes. One uses pre-calculated tabulated opacity data, so called opacity distribution functions (ODF). These ODFs are tabulated on a grid of temperature, gas and electron pressure and are available for a small number of pre-given element mixtures. (For details see Kurucz (1979).) A different approach, that treats "all" bound-bound transitions individually, and allows for a free choice in the mixture of species is the opacity sampling (OS) method. As our code exists as a ODF **and** as a OS version, the latter making use of a database of more than 20 million lines of the first three ionisation stages, we are able to compare between ODF and OS.

There are two major sources of continuous opacities: Free-free transitions and bound-free. While the photon scattering processes are quantum mechanically well understood, ionization was treated in simple hydrogenic approximations until recently, when detailed calculations of bound-free cross sections became available. Figure 1,(left) shows the difference between simple hydrogenic approximation and the detailed calculations of Bautista (1997) for four Fe I ionization energy levels.

Figure 1. Left: Comparison of simple hydrogenic (full black line) and detailed calculation for 4 different energy levels of Fe I. Right: Comparison between MAFAGS-ODF and MAFAGS-OS model flux for the standard solar model.



In the right part of Fig. 1 the comparison of the MAFAGS-ODF model with hydrogenic approximations and the MAFAGS-OS model with more detailed data and individual treatment of the line opacity is shown. It becomes clear, that color integrals are affected by the change in model. As the flux in the ultraviolet region is decreased, revealing what is called the *missing UV-opacity problem* flux is redistributed to the red. This affects the infrared flux method temperature determination.

For the solar model, the U-B/B-V color temperature changes by 170/45 K. The IRFM temperature is affected by 60 K and the change in temperature structure leads to a change in the temperature determined by Balmer line profiles of 50 K.

Treatment of convection Convection is a crucial issue in the treatment of stellar atmospheres. For stars with $T_{eff} < 10000$ K a large fraction of energy in the deeper layers of the atmosphere is transported by convective movement.

As we are only considering 1D hydrostatic atmospheric models we have the choice between a number of models to treat convection. There are the most simple models such as the one by Boehm-Vitense (1981) that allows for only one "type of bubble" and the more complex theories of Canuto & Mazzitelli (1991) that allows for a whole spectrum of *eddies*.
Both theories allow for a free parameter, that describes the *efficiency* of convection. This α-parameter of convection can be determined using the Balmer series (see Fuhrmann, Axer and Gehren (1993) and Castelli, Gratton & Kurucz (1997)). However this determination of α can not be done better than ± 0.15. Together with the insecure choice of the model this results in an error of approximately 10 K for IRFM and U-B/B-V colors and 30 K for the Balmer line temperatures.

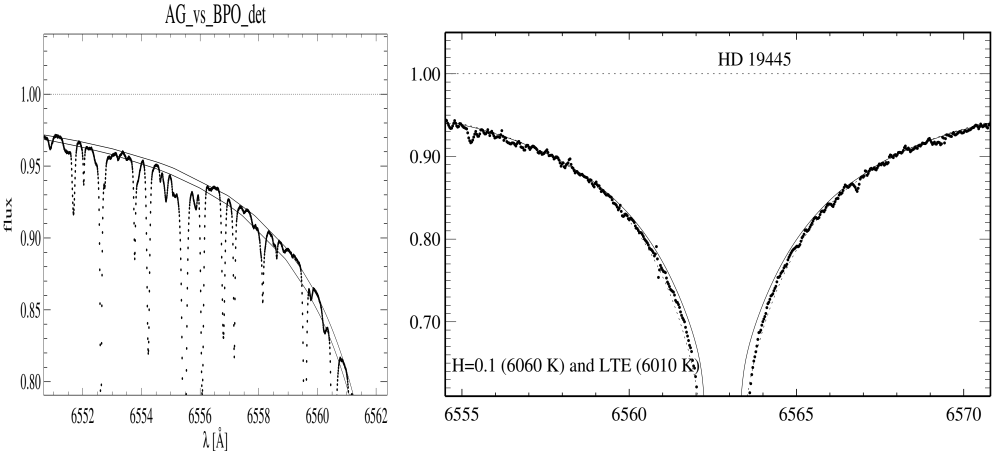
Solar element mixture As another source of uncertainty we can identify the element mixture of the sun. In several recent analysis the abundance of the CNO elements was "changed" (see several articles in these proceedings). Furthermore, the solar iron abundance is insecure by at least 0.03 Dex. These insecurities lead to possible errors in T_{eff} of 15 K for IRFM, 30/20 K for U-B and B-V color indices and 15 K for Balmer line temperatures.

2.2. Line formation

Balmer lines are a well tested method of determining stellar effective temperatures (see e.g. Fuhrmann, Axer and Gehren (1993)). This method comprises two extra sources of error.

First there are concurrent descriptions of resonance broadening. Figure 2 (left) shows the difference between Ali & Griem (1965) and the more recent work of Barklem, Piskunov & O'Mara (2000). Second, hydrogen shows departures from local thermal equilibrium in metal poor stars. Figure 2(right) shows calculations for the metal poor star HD19445 in LTE and Non-LTE. Neither of the profiles shows a perfect fit, but difference it the determined effective temperature of $\approx$ 50 K become obvious. This effect is minor in solar metallicity stars of the same temperature range.

Figure 2. Left: Comarison of Ali & Griem (1965) and Barklem, Piskunov & O'Mara (2000) profiles for the solar H_α line. Right: LTE versus Non-LTE H_α line of the metal poor star HD19445.



Together with the stated insecurity in the choice of the resonance broadening theory, we need to add an additional error of $\approx$ 60 K to the Balmer line temperature values due to line formation insecurities.

3. Error budget and conclusions

Summarizing the various sources of errors in tab. 1 it turns out to be impossible to simply sum up the errors. This is neither possible for simple sums nor for doing a quadratic sum, that would assume some Gaussian shape distribution in each source of the errors. This might become most obvious in case of the choice of the "proper" convection and resonance broadening theory. These bimodal choices

Table 1. Error budget for T_{eff} of a solar type star. The error source named "computation" is associated with a finite precision of convergence in the model atmosphere calculation process.

	IRFM	U-B	B-V	Balmer
Computation	10	10	10	10
ODF→OS	60	170	55	50
1D convection	10	10	5	30
CNO abundance	15	40	20	15
Fe abundance	30	30	25	25
Balmer line method				60
Quadratic sum	70	180	65	90
Total sum	125	260	115	190

are clearly non-Gaussian. Instead of summing up the single errors, we would rather suggest to look at tab. 1 in the sense of an **error budget**. It depends on the science case and the scientist what part of this budget he *spends*.
In a more general view it becomes obvious, that error bars assigned to stellar effective temperatures can hardly ever be smaller than 75 K.

Giving an outlook on how we can improve on this situation and get toward a better determined effective temperature we would suggest the following tests:

As Balmer lines probe a significant fraction of the stellar atmosphere. The consistency between the first 4 series members gives a great test to the models.

VLT-Interferometer measurements of nearby main sequence stars could provide us with more stars (other than the Sun) with "known" stellar parameters to test our methods and procedures.

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